advanced southeastward, and numerous snow squalls occurred within the air mass.

The density relations for Cheyenne and Omaha are illustrated in figure 11. The soundings at Scott Field, which would have been particularly interesting for this situation, were unfortunately not made, because of adverse flying conditions. However, the density curves for Cheyenne indicate less dense air on the 4th than had occupied the station on the 3rd. Some indication of the advance of the P_c air aloft is given by the fact that the slopes of the curves on the 3rd and 4th are such that the intersection occurs near the 5 km level. The hypothetical picture in figure 3D best illustrates these density relations. A very deep current of P_c air invaded Cheyenne on the 5th, and the density curve for that day shows the the greatest density, level for level, of the 3 days.

The density relations for Omaha on the 4th and 5th are especially significant. Denser air below 1,100 meters on the 5th indicates the depth of the P_c current. Between 1,100 and 3,000 meters the current becomes less dense than the air that prevailed at these levels on the 4th. Above 3,000 meters denser air on the 5th again prevails, compared with the corresponding levels on the 4th. This crossing of the density curves aloft is peculiar to the passage of the upper cold front and justifies the conclusion as to its presence.

May 18, 1936.—This situation was brought to the writer's attention by Warren Vine of American Airlines, who, flying from Murfreesboro to Washington between the hours of 1 p. m. to 5 p. m., encountered "a line of high level thunderstorms over the mountains." The line of storms advanced regularly eastward with a velocity comparable to that of the winds aloft. The bases of the cumulus clouds were generally above 8,000 feet, and lower clouds were encountered only during showers.

The synoptic situation is represented in figure 12. An upper cold front is present and virtually parallels the Appalachian chain. The interesting feature about this situation is that the upper front marks the advance of T_G air as a cold front. This condition frequently obtains when T_G air comes in contact with T_S air. The Maritime air is riding aloft over a very shallow thickness of highly modified P_c air, and is displacing T_S air that prevails aloft over the narrow wedge of old P_c air. During the day the air masses to the east of the upper cold front became considerably heated, and as the T_G air invaded the region a very unstable condition was produced. High-level thunderstorms developed during the afternoon with the advance of the upper front, and continued to accompany the front as it passed off the coastal regions during the evening. The storms developed in the advancing T_G air, as the T_S air was much too dry to produce any thunderstorm activity.

Figure 13 shows the density relations on May 17 and May 18 for Selfridge Field, Wright Field, and Murfreesboro. The curves are not as distinctive as one might desire; but the fact that all three stations show the advance of slightly denser air aloft, compared with that which prevailed at the same levels on the 17th, furnishes significant evidence of an upper cold front. The very shallow wedge of old P_c air is shown on the curves for the Selfridge Field and Wright Field soundings. At approximately 500 meters the curves intersect each other, indicating that below this level the advancing air on the 18th was less dense than the air on the 17th.

For all practical purposes the T_G cold front in this case may be considered as a surface front; but it is to be pointed out that surface information does not clearly define the front, and this example is a good illustration of the applicability of aerographic soundings to synoptic analysis.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to American Airlines, Inc., under whose employment this study was begun; to Warren Vine, John Pricer, Walter Hunter, and many other pilots of American Airlines, Inc., whose helpful observations furnished data to analyze difficult and complex situations involving upper cold fronts; to A. B. Bowman, N. D. Garrow, and W. E. Pereira, meteorologists of American Airlines, for their kind assistance in the calculations and plotting of soundings and preparation of the synoptic charts; to H. R. Byers, S. Lichtblau, and H. Wexler, of the Meteorological Research Division, U. S. Weather Bureau, for their helpful discussions and kind cooperation. He is especially grateful to Dr. Byers for invaluable criticisms.

UPPER-AIR COLD FRONTS IN NORTH AMERICA

By STEPHEN LICHTBLAU

[Weather Bureau, Washington, December 1936]

Fronts aloft have long been recognized, but until recently very little attention has been given to them. In the United States much of the weather, especially in the colder months, is governed by such fronts as well as by surface fronts. Although as many different types of fronts may exist aloft as at the surface, we find that of the three types of fronts—namely, cold, warm, and occluded—only the cold front has much significance aloft, and it is by far the easiest to locate. Warm fronts aloft may occasionally be located when they are accompanied by well defined synoptic phenomena; but usually the meteorological elements, with the exception of precipitation, indicate gradual changes rather than the abrupt changes found with the passage of cold fronts aloft.

Occluded fronts are identified as such from their past history, if possible, or with the aid of airplane soundings; the soundings should show a trough of warm air in advance of the cold front aloft. However, many of the fronts designated as cold fronts aloft may in reality be occluded fronts aloft, since in many cases the history of such fronts moving eastward across the Pacific, where few reports are available, is quite vague. Furthermore, if there is a trough of warm air associated with the cold front aloft, it may neither be apparent in cloud and precipitation forms nor fall within the network of airplane sounding stations; but occluded fronts aloft are in most cases so high that no significant error will ordinarily accrue if such fronts are designated as cold fronts aloft. The following discussion is therefore limited to upper air cold fronts.

FORMATION

Cold fronts aloft may in most cases be traced back to surface occlusions of the warm front type. One exception occurs with frontogenesis aloft above a shallow polar current, usually of continental origin. The considerations for frontogenesis are as applicable aloft as they are on the surface.[1] Another exception of a more complicated nature occurs as a development in the advance portion of a deep polar current, in the form of a steepening of the slope of the polar wedge at some distance behind the

[1] Petterssen, Sverre: Contribution to the theory of Frontogenesis, Geofysiske Publikasjoner, vol. XI, no. 6.

surface front. This implies either a decrease in wind velocity or a change in wind direction above the elevation where the slope steepens, in such a manner as to cause the lower portion of the air mass to advance more rapidly than the upper portion. The precipitation may at times be more pronounced with an upper air front formed in this manner than with the associated surface front. The reverse of the above process will explain the formation of most warm fronts aloft.

These exceptions, while often important, occur much less frequently than the cold fronts aloft found with warm type occluded fronts. The two general regions for the formation of occluded fronts of the latter nature, as far as United States weather is concerned, are in the Pacific Ocean at varying distances from our coast (depending principally upon the location of the Aleutian LOW) and along the mountain ranges from California to Alaska. When the occlusion of a warm sector of modified Polar Maritime air occurs at some distance from the coast we find, with the warm front type of occlusion, that the surface air is warmer to the west than to the east, which permits the air to the west to ascend over the colder wedge as it moves eastward. Aloft, however, in the air to the west we find low temperatures, sometimes exceedingly low with steep lapse rates that often approach the dry adiabatic lapse-rate characteristic of fresh outbreaks of Polar Pacific air.[2]

The diagrams in figures 1*a*, 1*b*, and 1*c* illustrate the formation of occlusions of this type. The surface occlusion which was originally the surface warm front may advance slowly or even remain stationary, while the cold front advances rapidly over the shallow polar wedge. The separation of these fronts may increase quite rapidly to a thousand miles or more. Also, the surface occlusion may have become insignificant from a synoptic viewpoint, remaining near the west coast, while the upper air front has traversed half the distance or more across the country, accompanied by considerable precipitation, the amounts of course depending upon the air masses encountered. In some cases, when the Pacific analysis is incomplete or inaccurate because of insufficient reports from ships at sea, it is impossible to find the surface front, especially if it is associated with a prominent upper cold front which has progressed far in advance of the surface occlusion.

The other general type of warm front occlusion which forms along the western mountain ranges needs no LOW nor even a well-pronounced trough for its formation: East of the mountains is a shallow surface layer of polar continental air which has been unable to spread westward because of the natural barrier presented by the mountains. This P_c air is usually very cold.[3] Above the P_c is found P_P which has gone through varying stages of modification, usually by means of subsidence. Fresh P_P air, with steep lapse rate, which comes in behind a surface cold front along the west coast, is colder than the modified P_P air and displaces it while moving eastward and ascending the mountains. After reaching the P_c air on the other side of the mountains it continues its movement as a cold front aloft, above and without displacing this P_c air, rather than as a surface front. The movement of such an upper air front will often be considerably accelerated after the retarding influence of the mountains has been overcome or left behind. Again, as in the other general case, the cold front aloft may advance rapidly across the country while the surface occlusion or surface warm front advances slowly or even remains stationary. The diagrams in figures 2*a* and 2*b* illustrate the formation of this type of occlusion.

Other occlusions of the warm front type may form anywhere over the continent.[4] With the type of warm front occlusion described by Wexler, however, the cold front often remains in close proximity to the surface occlusion as it advances across the country and seldom progresses so far ahead of the occlusion as in the other two types of cold fronts aloft.

LIFE HISTORY

The cold front aloft moves in most instances above a P_c air mass of average depth approximately 2,000 meters in the United States. This depth may vary considerably, from zero at the surface cold front in the advance portion of the P_c air mass to as much as 4,000 meters in the central portion under extraordinary circumstances.[5] Usually the cold front aloft encounters little resistance, and moves rapidly across the country without ever coming down to the surface; but occasionally waves and cyclogenesis will occur along the front, and by disturbing the surface pressure field may cause the front to be propagated to the surface. As a rule cold fronts aloft, with any disturbances that form on them, remain aloft in the western portion of the country, and descend or are propagated to the surface only after they pass the Mississippi River. The cold front aloft may come to the surface simply by overtaking the surface cold front at the forward portion of the P_c current that it had originally surmounted; in most such cases, the two fronts will then advance as one surface front with the velocity of the cold front aloft, but sometimes after the cold front aloft overtakes the surface front it will continue to move as a surface front and increase its distance from the P_c front. Since a descent of air over the forward portion of a polar wedge necessarily implies subsidence, it is apparent that the process just described could not be responsible for so much precipitation as had occurred before the beginning of the descent; but, by accelerating the P_c front, it could bring about lower temperatures much sooner than the forecaster would expect if he considered only the surface front.

In comparison with this process of simple descent, we find that a propagation downward to the surface is more complicated. The cold front aloft usually will be propagated to the surface when it comes over a surface pressure trough or field of convergence. The trough or field of convergence without a front may already be a good region for frontogenesis, with winds having a southerly component on the eastern side and winds with a westerly or even northerly component on the western side. The winds associated with the cold front aloft are more accentuated on either side of the front and will show a well-marked trough in the isobaric field at the top of the surface layer of cold air. When the pressure trough associated with the upper front becomes superimposed upon the surface pressure trough we find that a surface cold front forms, with well-marked wind shifts and other

[2] Byers, H. R. The Air Masses of the North Pacific, Scripps Institute of Oceanography Technical Series, vol. III, pp. 311-354.
[3] Wexler, H. Cooling in the Lower Atmosphere and the Structure of Polar Continental Air, MONTHLY WEATHER REVIEW, vol. 64, no. 4.
[4] Wexler, H. Analysis of a Warm Front Type Occlusion, MONTHLY WEATHER REVIEW, vol. 63, no. 7.
[5] Wexler, Loc. cit.

characteristics of such fronts. If vertical mixing has taken place, the surface cold front will be continuous with the upper front and there will be but one front. If little or no mixing has taken place, the cold front aloft will continue to advance aloft and will outstrip the surface cold front that it generated in the field of convergence. This type of frontogenesis, in contrast with the type which does not require the aid of a cold front aloft, can be anticipated much more confidently, because the progress of the cold front aloft can be followed quite accurately for sometime before it enters the region where frontogenesis is likely. It is the opinion of the writer that in most instances surface frontogenesis over the North American continent occurs with the aid of upper air cold fronts in the manner described above.

Cyclogenesis, or the intensification of a LOW, will take place if the cold front aloft encounters a stagnant or slow-moving surface cyclone. The cyclone will intensify and move rapidly along the upper-air front, which then becomes a surface cold front south of the center. Here again a knowledge of the movement of the cold front aloft is important to the forecaster.

The movements of cold fronts aloft can be determined with fair accuracy because such fronts are affected by frictional influences to a less degree than are surface fronts. The 3-hour pressure tendencies and the 12-hour pressure change chart are more useful as qualitative rather than as quantitative indications of the movements of cold fronts aloft. Unfortunately kinematic computations, except in isolated cases, have little meaning, because the pressure field on the surface map is governed to a considerable extent by the lower air. It is equally unfortunate that a cold front aloft in close proximity to a surface front will complicate the pressure tendency field to such an extent that rigid kinematic computations made on the surface front will produce fallacious results. It has been found that the winds aloft, when they are available, within the air mass behind the cold front aloft will give the most reliable quantitative determination of the movement of the cold front aloft.

It has been found that cold fronts aloft are sometimes confused with fronts formed by frontogenesis, especially in regions where weather reporting stations are far apart. For example we often find in northwestern Canada two well-developed HIGHS separated by a trough, where on earlier maps there was but one HIGH. The previous history of these HIGHS may not show a surface front in the trough, although there now are good indications of a cold front of some nature. The pressure tendencies west of the trough will show well-marked rises, while east of the trough the pressures are falling. This region, even with a well-developed trough, may not have a temperature distribution in the low levels favorable for frontogenesis. If conditions are not favorable for frontogenesis, it is logical to conclude that if there is a front in the trough it must be a cold front aloft which could have been traced back to the Pacific on previous maps had sufficient data been available. Such a history could not be found for a front formed by frontogenesis in the Canadian Northwest. If, on the other hand, conditions are favorable for frontogenesis, we find that a surface front will be formed and will usually move slowly in this region, while a cold front aloft will continue its rapid movement.

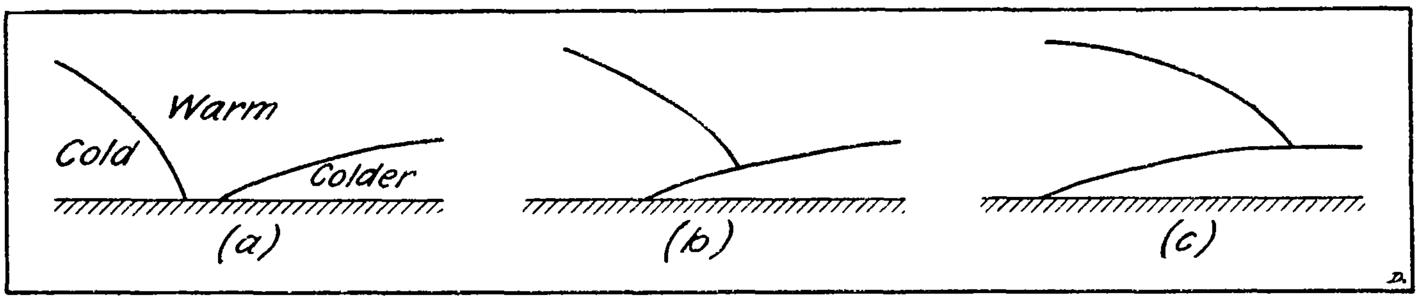


FIGURE 1.

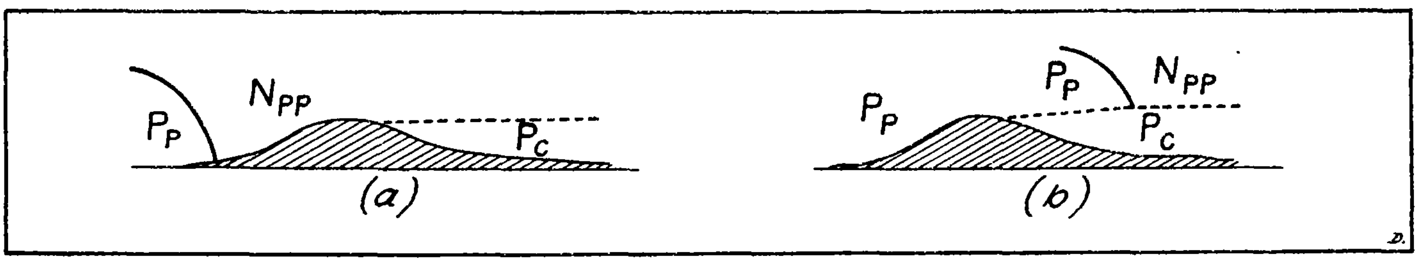


FIGURE 2.

RECOGNITION AND EFFECTS

A cold front aloft is at times easily detected and located on the surface map, while at other times its location becomes indefinite. If the processes of formation from occlusion have been observed, either over the Pacific Ocean or in the mountain regions, there is less difficulty in finding the cold front aloft, since it is expected. Difficulties arise when the formation is not observed. We then become aware of the front either from upper air data or from surface indications. The cold front aloft will have little influence on the surface temperatures as long as it remains aloft. It is not unusual to find the surface air moving in a direction opposite to that of the air aloft behind the cold front. The surface isobars along the cold front aloft will show a trough with no sharp discontinuities at the front.

Pressure tendencies afford the best clue for both the recognition and the determination of the progress of the cold front aloft. The forms of precipitation characteristic of P_P air when it is unstable will be observed falling through the shallow surface P_c air mass. In the advance portion of the front there may be considerable precipitation if the air mass in advance is moist and is forced upward. The front then resembles a surface cold front in many respects, but cannot be a surface front because it moves against the surface gradient and consequently against the surface winds. Airplane observations not only substantiate, but often reveal, the existence of the cold front aloft before its effects are observed on the surface map. There is always an increase in potential temperature and usually a well-marked temperature inversion at the surface or zone of separation between the surface air and the air above which has come in behind the cold front aloft. Also the cold air aloft contrasts sharply with the warmer air which it is displacing.

The foregoing discussion has been limited to the simple cases which occur during the colder months of the year, when cold fronts aloft are most frequent and most prominent. Such fronts do exist throughout the year, and may involve the juxtaposition of any group of air masses. The only condition necessary is that the lower air mass have at all elevations a greater density than the upper air mass.

The exceedingly cold air behind the front in Montana can be nothing but P_c which is part of the same air mass that is found east of the front in the Dakotas, Nebraska, Kansas, and Oklahoma.

Three airplane observations made on this day—one at Spokane at 4 a. m., one at Seattle at noon, and one at Cheyenne at 4 a. m.—conclusively demonstrate the existence and progress of the cold front aloft. The temperatures at all levels at Spokane and at Seattle dropped as much as 16° C. at 4,000 meters during the previous 24 hours, while the changes at Cheyenne, in advance of the front, were negligible in that period. At Spokane the very low temperature of −40° C. was observed at 5,300 meters. Seattle, where the observation was taken 8 hours later, had somewhat higher temperatures because at that time it must have been in the rear and warmer portion of the P_P air mass. In figure 7 the top of the surface P_c air mass is marked at Spokane by an isothermal layer throughout which the winds shift from NE. to NW. with increasing elevation; while at Seattle the P_c air is limited to the top of the isothermal layer at about 2,600 meters.

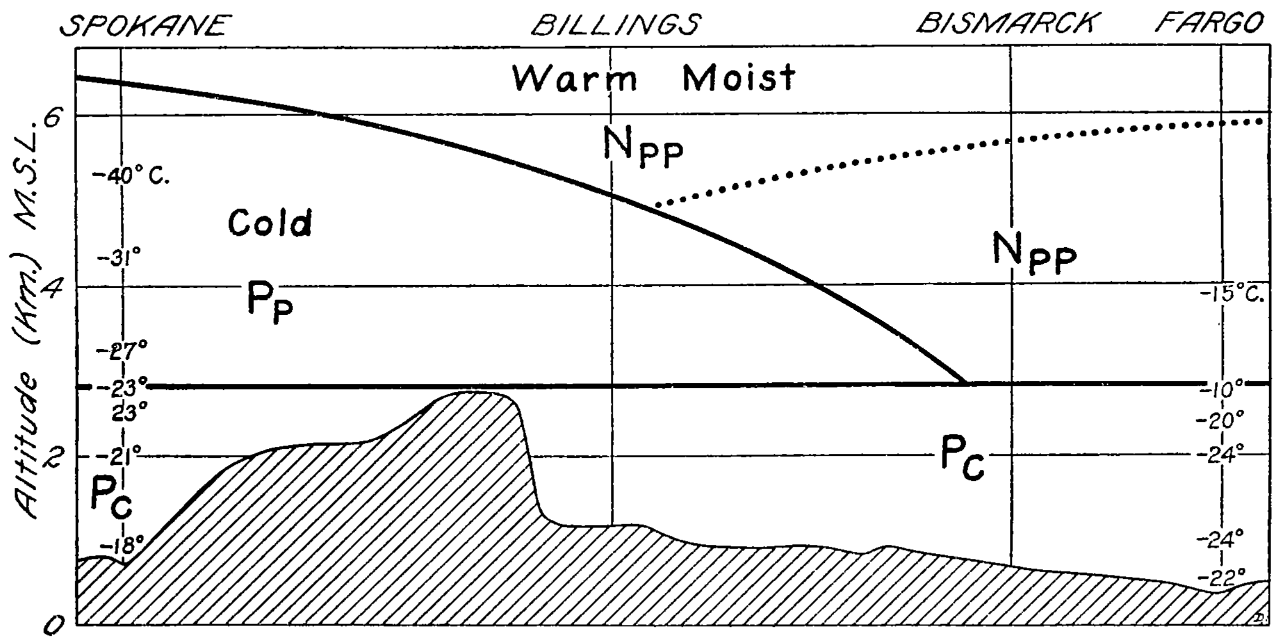


Figure 3.—Vertical section, Spokane-Fargo.

In the summer months it is not unusual to find warm moist Tropical Maritime air behind a cold front aloft. In such a case the surface air mass is a modified Polar air mass, while very warm "Superior" air is found over the Polar air in advance of the T_M front aloft. An interesting situation of this nature is discussed in the contribution by B. Holzman in this issue of the Review, p. 400.

EXAMPLE

A well-developed cold front aloft appeared on the 8 a. m. map of February 13, 1936. Although this particular front was not well marked on previous maps, its movement could be observed after it formed from a warm front occlusion in the Gulf of Alaska. Even a cursory examination of the pressure tendencies on the 8 a. m. map of February 13 indicates a front of some nature, with Williston and Rapid City on one side and Bismarck and Valentine on the other side; and an inspection of previous maps shows that the front had been moving eastward against the prevailing surface pressure gradient. There is little difference in temperature on either side of this front. Unfortunately, no airplane observation was made at Billings on this day.

South of this front there is another cold front aloft, which came in on the coast from the Pacific as a surface P_P cold front and became a front aloft after surmounting the shallow N_{PP} air mass ahead of the occluded front. The nature and progress of this cold front aloft had been detected and followed by indications from surface data, since no airplane observations were available at that time in that region. Again the principal evidence lies in the pressure tendencies at Grand Junction on one side of the front, and at Cheyenne, Denver, Pueblo, and Santa Fe on the other side. It is interesting to note the thunderstorms that occurred at Salt Lake City, Phoenix, and San Diego in conjunction with the front while it was still a surface front. These two cold fronts aloft are associated with two different air masses, with the one to the north much colder. It is merely a coincidence that the P_c surface front lies in the region where the two P_P air masses are in juxtaposition aloft.

The schematic vertical cross sections in figures 3, 4, 5, and 6 are presented in order to enable one to visualize a three-dimensional picture of the upper air corresponding with the first surface map of the series. The warm moist N_{PP} air indicated on some of these sections must have existed at that time over only a small region and at comparatively high levels, since it was never actually found in any of the airplane observations although its progress could be observed with little difficulty on the surface map. The thunderstorms and the large amounts of precipitation in the Southwest show that such an air mass must have been present in advance of the P_P front. The cross section through Spokane, Cheyenne, and Omaha (fig. 7) shows this air to be apparent in conjunction with the altostratus clouds; and such an air mass is indicated at high levels in the vicinity of Billings.

We see then that we can account for most of the precipitation in the Southwest, except that occurring in California, with the aid of the moist N_{PP} air. This same air mass will account for some of the precipitation in the vicinity of the northern cold front aloft. Most of the precipitation, however, is occurring within the unstable P_P air mass itself, as evidenced by the snow flurries reported at some of the stations. The precipitation far in advance is not associated with either of the P_P fronts, nor with the warm moist N_{PP} air mass, but rather with a frontal system centered in Illinois.

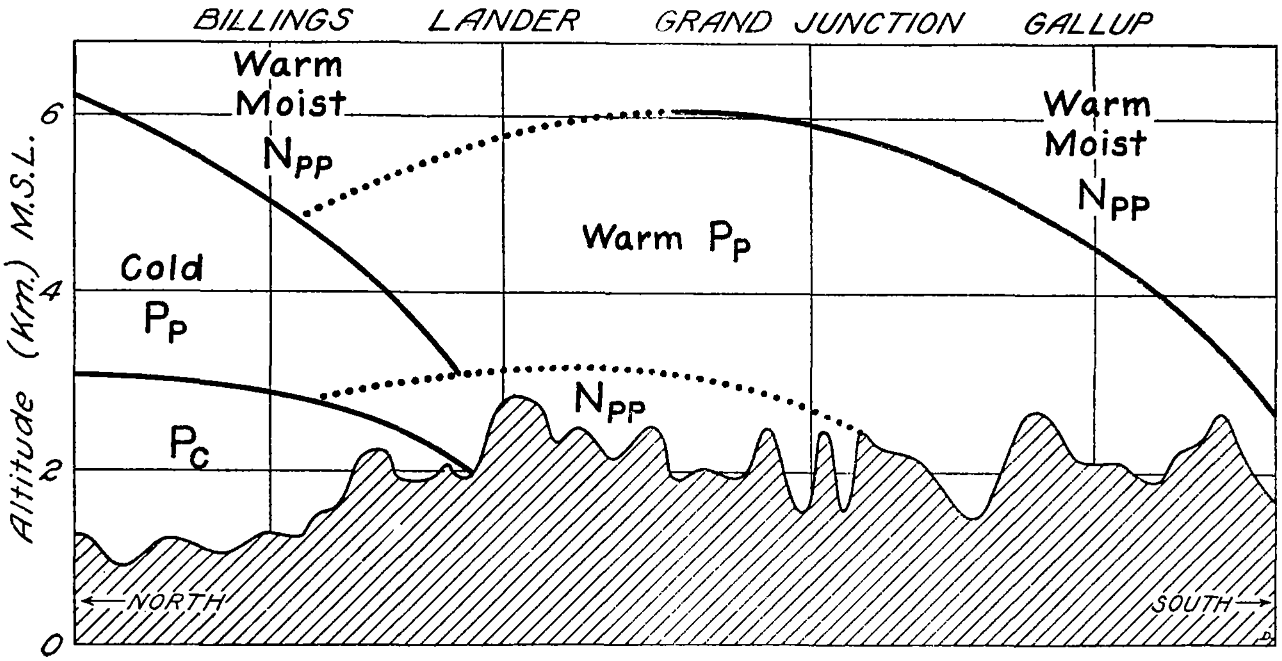


FIGURE 4.—Vertical section along the 109th meridian.

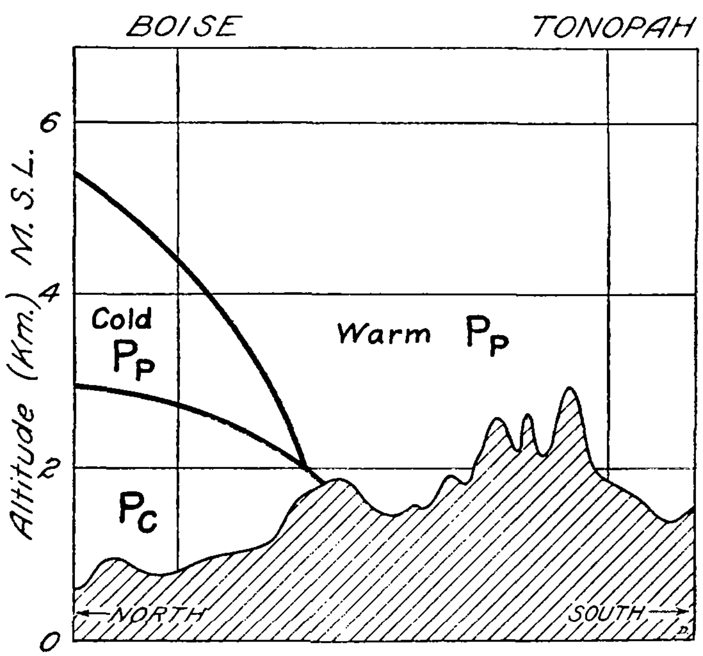


FIGURE 5.—Vertical section along the 117th meridian.

On the next map of this series (2 p. m., Feb. 13), we have little trouble finding the fronts. Observe the rapid movements of both cold fronts aloft, and the progress of

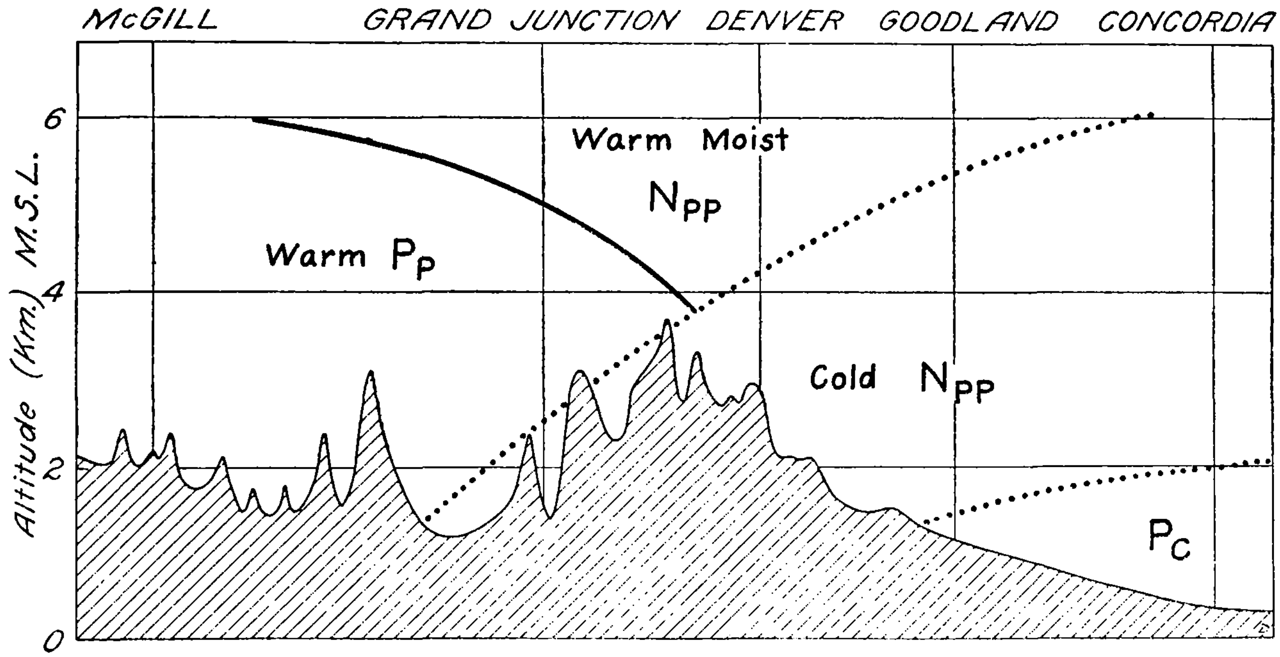


FIGURE 6.—Vertical section along 39th parallel of latitude.

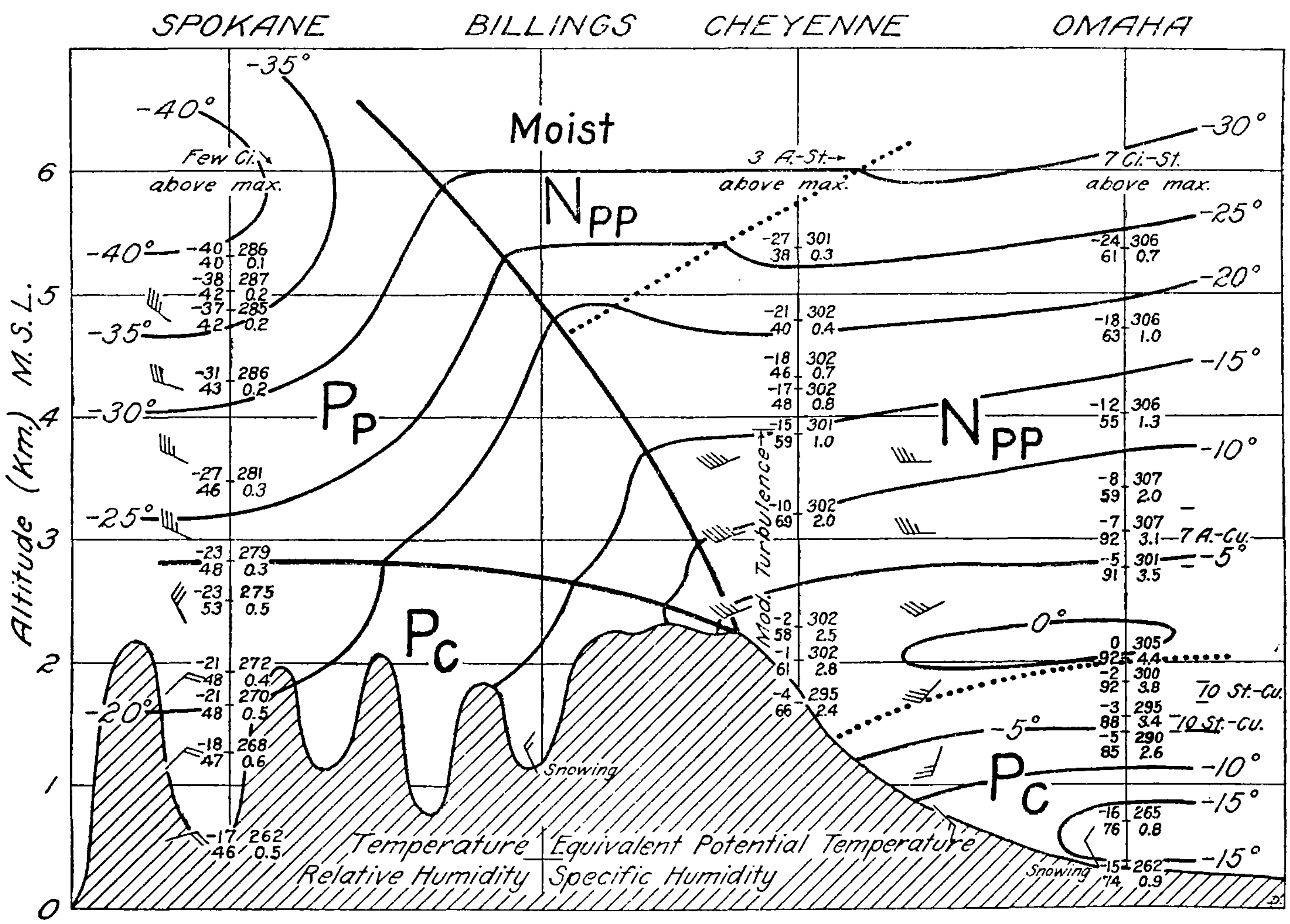


FIGURE 7.—Vertical section, Spokane-Omaha.

the P_c front at Lander where the temperature dropped 44° F. in 6 hours. The occluded front associated with the southern P_P front has moved more rapidly than the front aloft; this is explained by the considerable turbulence and consequent mixing within and between the shallow N_{PP} air and the P_P air above it and is substantiated by the heavy dust reported at El Paso, where there has been a front passage, and at Amarillo still in the N_{PP} air. The mixing between the shallow N_{PP} air and the P_P air above destroys the front between them and displaces the surface front to the east where the N_{PP} air is deeper and less mixing occurs. Such mixing brings the potentially warmer air from higher levels down to the surface. In comparing the temperatures on either side of this occluded front it must be remembered that the stations to the west are at a much higher elevation than those to the east of the front, and that the lapse rate within the N_{PP} air after midday must be very close to the dry adiabatic and may even be slightly in excess of the dry adiabatic close to the surface.

On the 8 p. m. map the same rapid movements continue. The northern cold front aloft continues as such above the P_c air, and is fast approaching the surface P_P cold front which has had little movement on previous maps. The movement of the southern cold front aloft is very well shown by the thunderstorm which occurred at Abilene between 5 and 6 p. m., and another one at Dallas which began at 7 p. m. and is continuing at the time of the observation. It is interesting to note the temperature changes during the day at Goodland, Kans. Goodland at 8 a. m. was in the P_c air with a temperature of 2° F. By 2 p. m. Goodland had been passed by the almost stationary warm front, with a resulting rise in temperature of 44° F. By 8 p. m. the temperature there dropped to 0° F., and we again find Goodland in the P_c air which has moved southward along with the rapidly moving P_c cold front aloft. On the 8 p. m. map the fronts on the extreme eastern portion of the map, which have been complicated by an active cyclone along the east coast, are omitted since they do not enter into this particular discussion.

The 2 a. m. map of February 14 again shows the rapid advance of the cold fronts aloft; the northern one has now almost overtaken the slow moving surface P_c front. A warm front aloft has been introduced south of Cleveland, indicating a very shallow layer of colder air between it and the surface warm front. The effective warm front is actually the upper front, where the slope of the cold air steepens and in advance of which we see the greatest pressure falls and precipitation. The temperature increase occurs behind the surface warm front.

On the 8 a. m. map of the same day we find that the northern cold front aloft has overtaken the surface P_c front and there is only one front, which is moving more rapidly than the P_c front had moved at any time during its history over the United States. The rapid movement continued for 12 hours, after which the structure of the front changed appreciably when it became influenced by other air masses in a region of considerable activity along the east coast. The northern part of the front which is still designated as a cold front aloft is now in a region which is well adapted for frontogenesis because there is now a favorable discontinuity in temperature at the surface on either side of the projected position of the front aloft. Frontogenesis did occur, and on later maps the front aloft was designated as a surface front.

The air behind the southern P_P front aloft has warmed by subsidence to such an extent that it has found no difficulty in going over the highly modified shallow polar air at the surface in the Southeast and displacing the Tropical Maritime air aloft and in advance of the P_P front. Again the passage of the front is well marked by thunderstorms at Shreveport, New Orleans, and Pensacola. The front continued on later maps as a cold front aloft with its attendant thunderstorms.

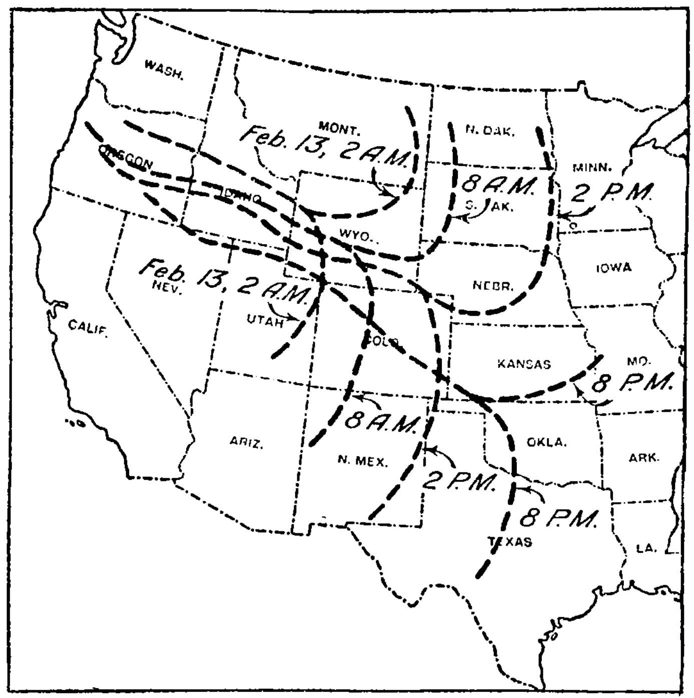
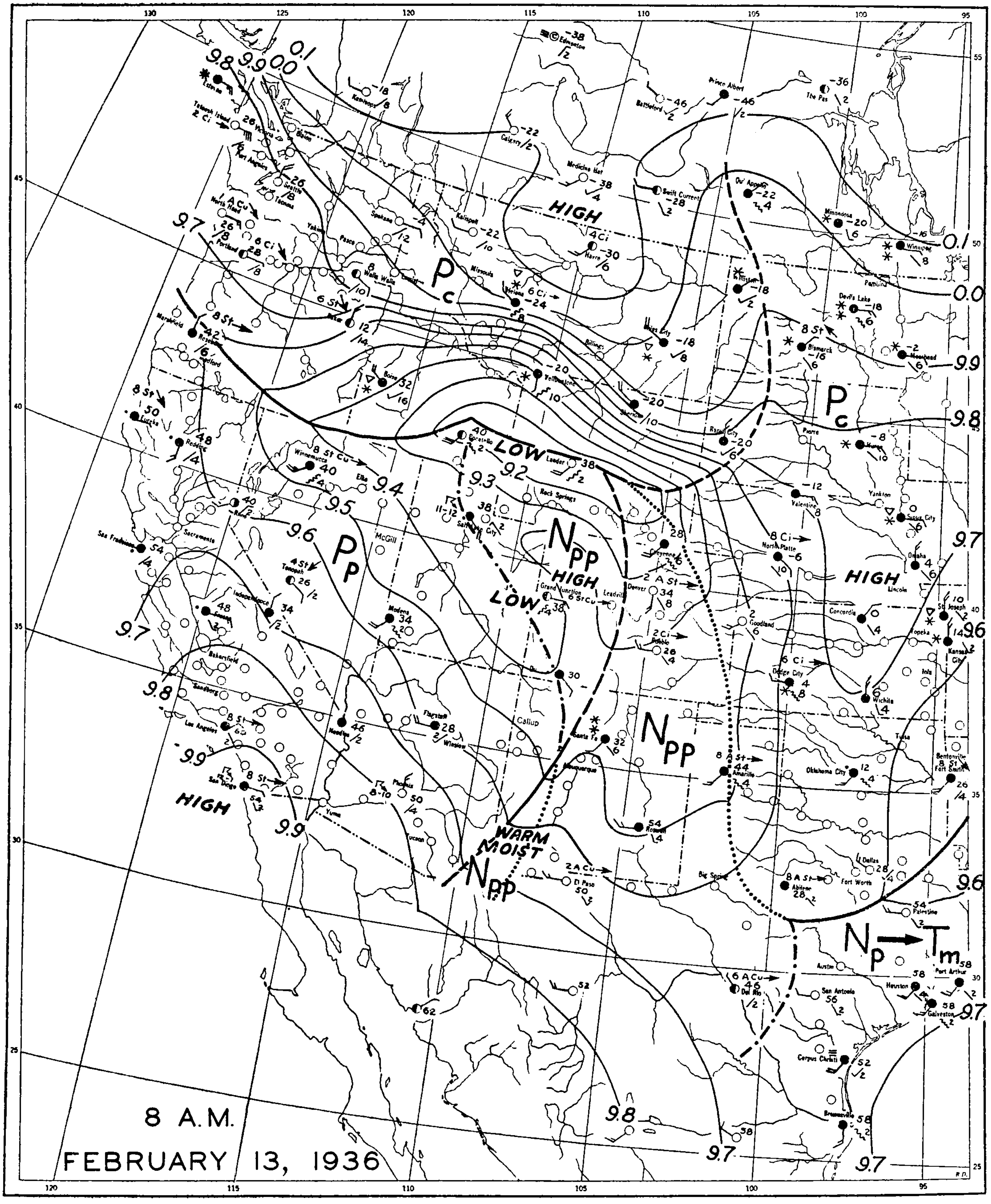
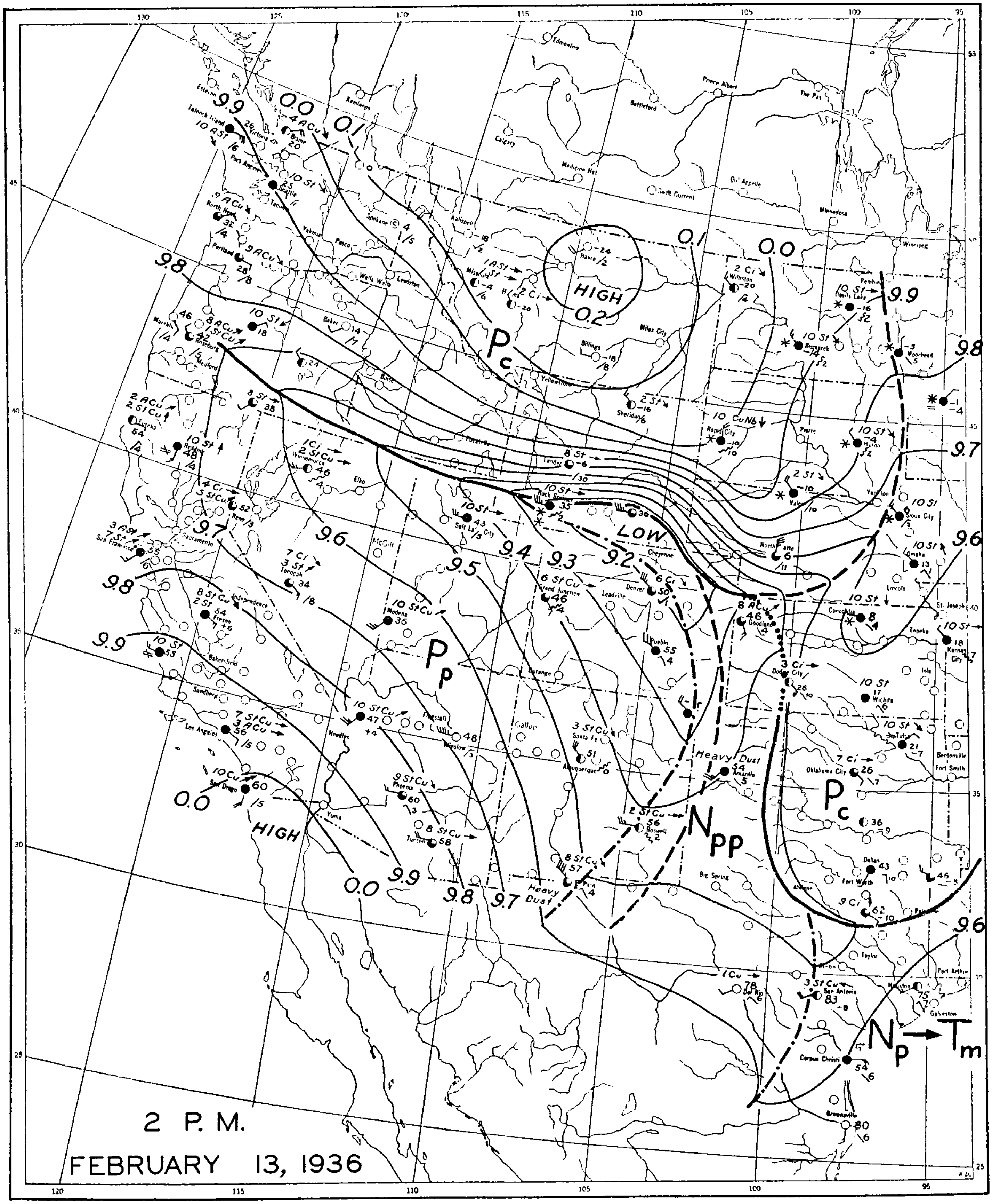
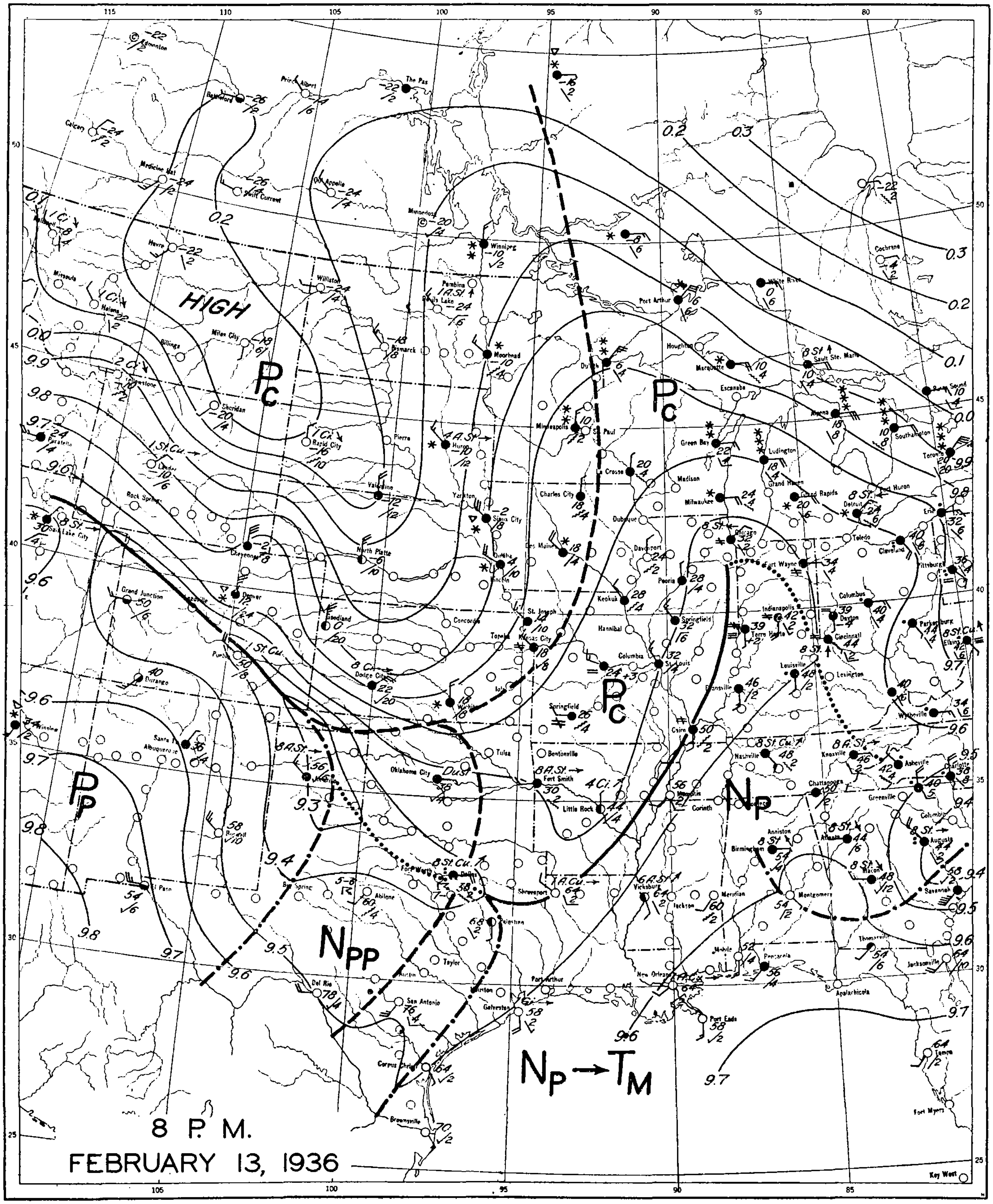


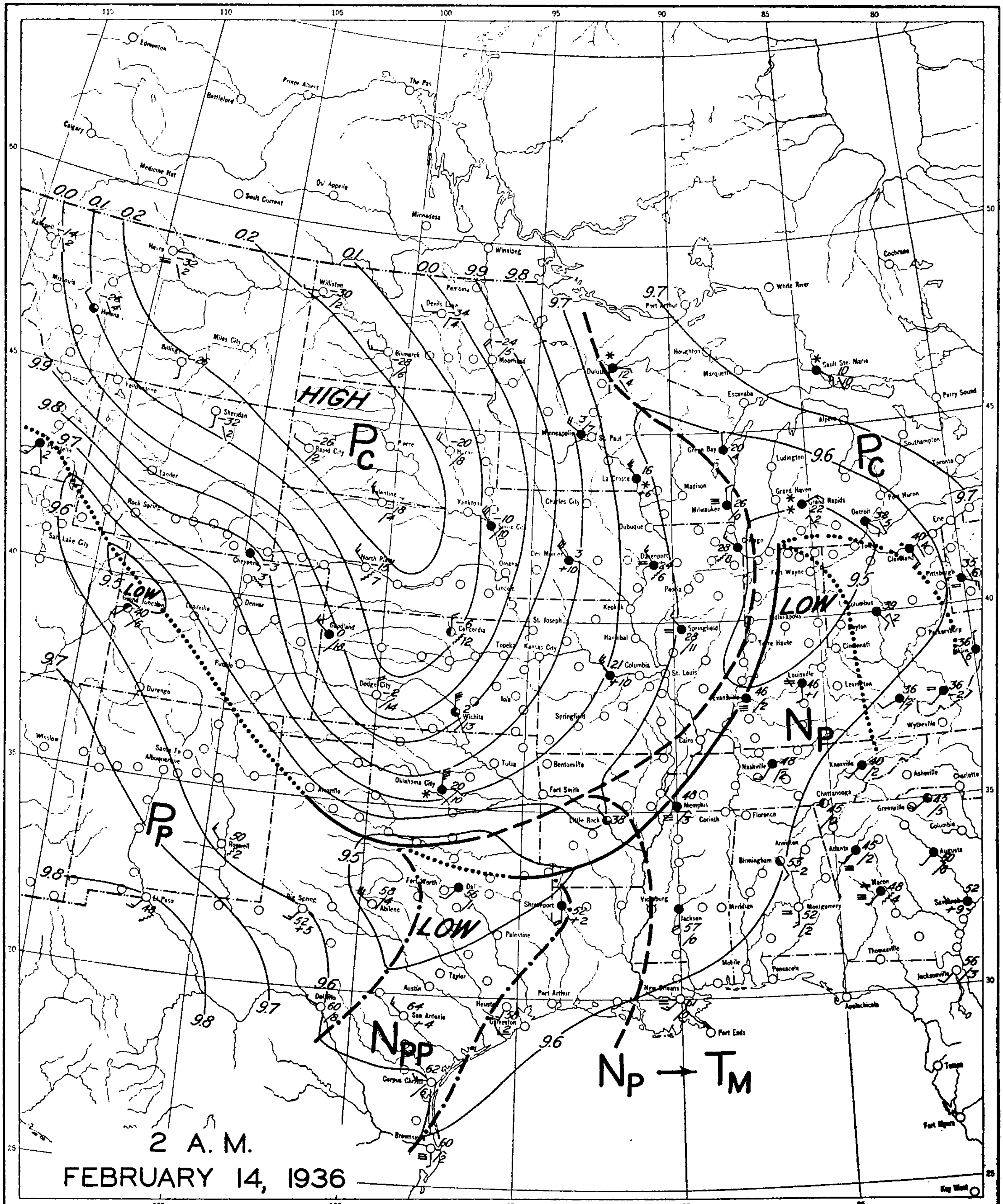
Figure 8.

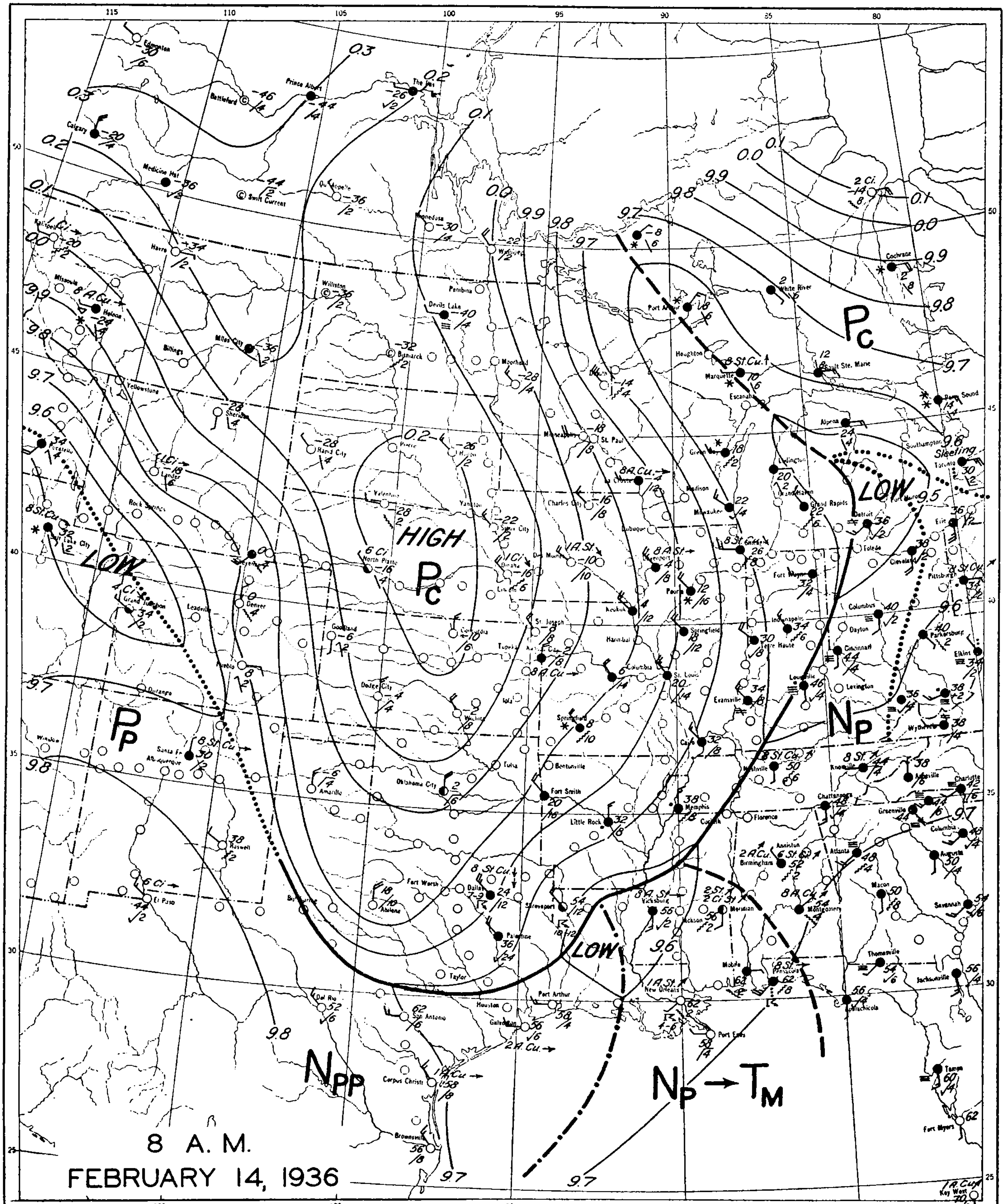
A composite map showing the movements of the P_P cold fronts aloft at the 5,000-foot level is given in figure 8. The 5,000-foot pressures available for the western part of the country at stations where the reduction to the 5,000-foot level does not involve a difference in elevation of more than 1,500 feet, and the available winds at 6,000 feet, were used for the determination of the location of the fronts in each 6-hour period. The positions of the northern front closely approximate the positions given on the corresponding surface maps, while the positions of the southern front fall behind the surface positions in the later stages which indicates only a slow increase in the depth of the southern P_P air mass as one goes westward. These fronts are not shown after 8 p. m. because they fall outside of the network of stations that reported 5,000-foot pressures.


HIGH
HIGH
HIGH
HIGH
LOW
LOW
WARM
MOIST
8 A.M.
FEBRUARY 13, 1936


2 P. M.
FEBRUARY 13, 1936
HIGH
LOW
HIGH
Pc
Pp
Npp
Pc
Np→Tm
Heavy Dust
Heavy Dust


HIGH
Pc
Pc
Pc
Pp
NPP
NP
NP → TM
8 P. M.
FEBRUARY 13, 1936


HIGH
LOW
LOW
LOW
LOW
P_C
P_C
P_P
N_P
N_{PP}
$N_P \rightarrow T_M$
2 A. M.
FEBRUARY 14, 1936


HIGH
Pc
LOW
LOW
LOW
Pp
Pc
Np
Npp
Np → Tm
8 A. M.
FEBRUARY 14, 1936